LCA Methodology

# A New Approach for a Modular Valuation of LCAs

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**Abstract**

**Goal Scope and Background.** Qualitative valuation methods carefully try to avoid an aggregation across impact categories. However, such an aggregation often helps in obtaining a clear result for the valuation (which product scores better?). This article presents a new valuation method that uses an iterative approach. The application is demonstrated by the help of a case study for electric motors in trains.

**Methods / Main Features.** The approach combines two existing, unique valuation methods described earlier in literature, which both are of a rather non-aggregating nature, in line with ISO requirements, and were designed to be performed by LCA experts. The method is implemented in a computer software. Besides constants used within the method, the software needs as input solely indicator values from the Impact Assessment.

**Results and Discussion.** The iterative nature of these methods itself, and especially the combination of these methods, helps in achieving a valuation result for the LCA with not more subjective and aggregating elements than necessary. Subjective elements are clearly separated from others. The algorithm seems highly sensitive to changes in impact categories regarded as important ones. The implementation in software greatly eases the application of the method by transferring routine work from LCA experts to a machine. It ensures a reproducible result and prevents erroneous steps in a rather complicated valuation procedure. It further helps in hiding the complexity of the method from the user.

**Conclusion.** The approach of combining valuation methods in LCAs seems a fruitful one, and shows benefits when implemented in computer software, in terms of usability, and in terms of a more reproducible application. Care has to be taken to make sure users know what they do when performing an automated valuation procedure.

**Outlook.** We see three ways for extending the approach, namely: (i) become part of a toolbox of different valuation procedures; (ii) explicitly cope with uncertainty, and (iii) include different values for normalisation, in different regions worldwide. The software will be made available also in a stand alone version.

**Keywords:** Grouping; modular approach; ranking; semi quantitative valuation; subjectivity interface; tool; toolbox

## 1 Introduction: Aims and Problems of a Valuation in Life Cycle Assessments

LCA as an ecodesign tool is often used to support decisions on products and services. To be able to reduce the environmental impacts related to a product (for example by switching to another product, or by changing the product itself), a comparison of alternatives is most interesting, a comparison yielding a ranking of the alternatives compared. In LCAs, this ranking is often difficult to obtain. If an impact assessment on midpoint level (Udo de Haes et al. 1999) has been performed, frequently some indicator results favour one alternative, and some the other. For example, product A has less climate change potential, while product B has a lower ozone depletion potential: How does the ranking look like, then?

Basically, the aim of a valuation may be seen in that it provides and compares the values of the objects considered. Commonly, a method pursuing this aim needs subjective elements to be introduced in its procedure for assigning these values (Finnveden 1997). These subjective elements give reason to suspect whether the scientific validity of the result is violated, and this 'suspicion' may be addressed as a common problem of valuation methods within LCA.

From the different valuation methods available (Ecosite 2002, Bengtsson 2000, Hildenbrand 1999), it can be observed that methods differ in where, at which place, and to what extent they make use of subjective elements, and also in the result they give. Some approaches provide not only rankings (as ordinal results), but quantitative results. On the one hand, these methods further assist in decision making by transforming complex results into easy to understand statements. But on the other hand, these results will be more assailable than rankings, because of the additionally used subjective elements. For an advanced discussion of advantages and disadvantages see (Udo de Haes et al. 1999, Finnveden 2000).

The international standards, especially ISO 14040 and ISO 14042, name two different types of valuation methods: grouping and weighting. Both grouping (sorting and ranking of impact categories according to their environmental importance) and weighting (using numerical factors for converting indicator results of different impact categories leading to a single score) (ISO 2000) are based on value choices including subjective elements (Udo de Haes et al. 1999). According to ISO, grouping and weighting are optional elements of the life cycle impact assessment (LCIA), and their use is restricted to internal LCAs. The most important requirements on grouping and weighting mentioned in ISO 14040 and ISO 14042 are transparency of procedures and (intermediate) results, and consistency of the procedures with goal and scope of the study (ISO 2000).

The procedure of performing grouping or weighting is not specified in the international standards. A standardisation

would make sense since recent works showed a considerable influence of the valuation procedures on the overall outcome of an LCA, due to the valuation procedure itself, but also due to the subjective elements introduced in a specific valuation procedure (Hildenbrand 1999, Ciroth 2002). In this article, after an overview of valuation methods, a new method that uses an iterative approach is presented and discussed from a methodological point in chapter 2. In chapter 3, the method is demonstrated in a case study, yielding new discussion points from the practical application.

### 1.1 Overview of valuation methods

Since 1990, several valuation methods for LCA have been developed and used for a large number of case studies (Hildenbrand 1999). For a comprehensive description and valuation of different methods see (Bengtsson 2000).

The methods may be structured into different sets (**Table 1**). The main difference is the type of result the methods provide: a single score (quantitative method) or an ordinal ranking (semi-quantitative or qualitative method).

The methods mentioned as examples in Table 1 will be discussed very briefly in the following.

**Table 1:** Overview of ranking methods

| Ranking method | Results | Example |
|---|---|---|
| Distance-to-target methods | single score | Ecopoints of BUWAL (Brand et al. 1998) |
| Endpoint-oriented impact assessment methods | one or several scores | Eco-indicator 99 (Goedkoop et al. 1998) |
| Quantitative weighting | single score | Panel methods (Bengtsson 2000, Giegrich et al. 1995) |
| Semi-quantitative weighting | ordinal ranking | UBA method (Giegrich et al. 1995) |
| Hierarchical approaches | ordinal ranking | CAU method (Volkwein, Gihr and Klöpffer 1996). |

#### 1.1.1 Method of environmental scarcity / Ecopoints of BUWAL

The method of environmental scarcity has been developed at the Swiss federal environmental agency BUWAL in 1990 (Brand et al. 1998) as one of the first valuation approaches. It allows a comparative weighting and aggregation of various environmental interventions by use of 'eco-factors' based on life cycle inventory results. No impact assessment according to ISO 14042 is included, but the most important impact categories are covered by this method indirectly.

Basically, the method uses a distance-to-target approach by comparing the actual pollution (current flows) in the inventory with critical flows (critical loads) which are deduced from the scientifically supported goals of the Swiss environment policy (Brand et al. 1998).

For emissions and energy sources weighting factors ('eco-factors') are calculated for different paths into the environment (air, surface water, ground water, soil) as follows:

$$\ddot{O}F = \frac{UBP}{F_k} \cdot \frac{F}{F_k} \cdot c \qquad \text{(Brand et al. 1998)} \qquad (1)$$

with:
- ÖF: eco-factor
- UBP: Environmental burden score
- F: current flow per year
- $F_k$: critical flow per year
- c: constant ($10^{12}$/a for better handling of results)

Eco-points representing the quantified environmental burden of an emission can be calculated via:

$$EP = \ddot{O}F \cdot m_i \qquad (2)$$

with:
- EP: eco-point
- $m_i$: emission of substance i (mass) related to the functional unit

As the final step, the eco-points are aggregated over all substances. Other distance-to-target approaches are discussed in detail in (Seppälä and Hämäläinen 2001).

#### 1.1.2 Eco-indicator 99

The Eco-indicator 99 has been developed by an international group of LCA and environmental experts mainly from the Netherlands and Switzerland as a 'damage oriented' impact assessment method (PRE 2000), based on the Eco-Indicator 95 impact assessment methodology (Goedkoop 1995). The aim was to develop a method to express the total environmental burden of a product in a single score (Goedkoop et al. 1998).

The damage function represents the relation between the impact and the damage to human health or to the ecosystem as impact assessment end-points. The main idea is to combine different impact categories into three areas of damage:

- Damage to mineral and fossil resources
- Damage to ecosystem quality
- Damage to human health

In order to get a single impact factor for each emission or resource, a weighting across the three areas of damage is performed.

The Eco-indicator 99 concept provides three sets of weighting factors according to assumptions concerning the time frame and other model choices. One set based on modest assumptions is used as a default by the authors of the Eco-indicator 99 ('Hierarchist' version).

The so-called weighted damage factors are substance specific and can be used analogous to the impact assessment factors in midpoint impact assessment:

$$EI99 = \sum_i m_i \cdot EI99_i \qquad (3)$$

with:
- EI99: Eco-indicator 99 score
- $EI99_i$: weighted damage factor of substance i

It is worth noting that the subsequent steps of the EI 99 method entail an increasing subjectivity, which thus rises from the characterisation, to the damage modelling, and, finally, to the weighting and normalisation.

### 1.1.3 Panel methods

In general, panel methods are based on judgements of experts or stakeholders. Individual ratings of the panel members are compiled to a common assertion. Quantitative weighting methods based on panel methods use a value benefit analysis approach: each impact category receives a 'weight'. After performing an impact assessment with indicator results for all impact categories, the impact categories are evaluated using individual weighting factors (e.g. values between 1 and 10). This evaluation of impact categories is, of course, mainly based on subjective values and is performed by an expert panel using questionnaires. These values can be based on legislation, market research, or monetary valuation (Schmidt and Sullivan 2002).

An aggregation of all impact indicators can be performed after their weighting (multiplying the indicator results and the weighting factor).

### 1.1.4 UBA method

The UBA method (UBA: German Federal Environmental Agency) provides an ordinal ranking as result (**Fig. 1**). Analogous to panel methods and quantitative weighting methods, a (midpoint) impact assessment and a valuation of the impact categories are performed separately (see Fig. 2). The main difference to panel and weighting methods is the semi-quantitative merging of both impact category indicator results and of the valuation result of each category in order to get an ordinal ranking.

The main ideas of the UBA method were presented in 1995 by (Giegrich et al. 1995). The German case study on drinks packaging system developed and used the method for the first time (Schmitz, Oels and Tiedemann 1996). A slightly modified version has been used in the update of the case study on drinks packaging systems (Plinke et al. 2000).

To balance the environmental burdens related to two alternatives to be compared, the ecological importance of the different impact categories has to be estimated. For this valuation the following – not independent and not measurable (Hildenbrand 1999) – criteria are used:

- Hazard potential: intensity of impacts for the safeguard objects concerned
- Temporal aspects: temporal range of the effects, reversibility or irreversibility
- Spatial coverage of the effects (from local to global)
- Preferences of the citizens (according to social science studies)
- Relation of current and previous environmental damage to environmental quality objectives (qualitative distance-to-target-approach).

For each impact category, these five criteria are used to receive a semi-quantitative valuation of each impact category using a five-stage scale (low importance to very high importance). This valuation is partly based on scientific findings. Subjective elements cannot be avoided in the choice of criteria, in the valuation of impact categories using the criteria, and also in the overall valuation of impact categories. To give an example for the results obtained, with the 'default

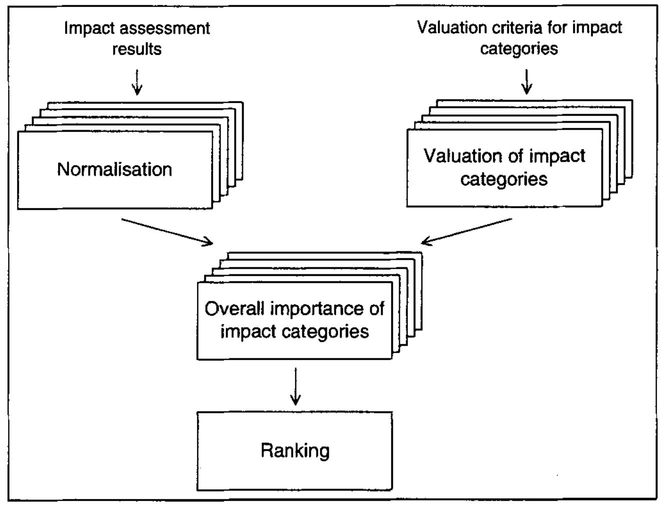



**Fig. 1**: Overview of the UBA method

settings' as described in (Giegrich et al. 1995), climate change is rated to be of very high importance, and resource depletion to be of high importance. This valuation is permanent, and does not depend on case study results.

On the other side, the impact indicator results per category are normalised, and then also converted into a five-stage scale using the highest value of all normalised impact indicators as reference. The result is called 'z value' and expresses the quantitative importance of each impact category for each alternative compared within the valuation.

Both elements, the importance of the impact categories and the normalised impact indicator results, are merged to an overall importance of each impact category by using a symmetrical matrix (Example: 'high' as category importance and 'very high' as quantitative importance gives 'very high' as overall importance).

Finally, in the last and most important step, the impact categories can be directly compared with each other. The aim is to find an alternative that scores better in 'overall more important' categories, and to eliminate categories where this alternative scores worse. In this process, categories of the same overall importance, but with different 'winners' (i.e. with different alternatives that score better in this category), can be eliminated against each other in order to get a clear ranking.

### 1.1.5 CAU method

This valuation method has been developed within a German research project (Fleischer et al. 2000). For a detailed description see (Volkwein, Gihr and Klöpffer 1996).

As the main idea, the prioritisation of impact categories including normalised indicator values is used. Similar to the UBA method, impact categories are valuated using valuation criteria, but without providing a single value for each category.

As the first step, the impact assessment results are normalised. The method is designed for performing a valuation of a pair, i.e. of two alternatives. For these two alternatives the difference for each impact indicator is calculated.

Within the next step the impact categories are valuated using five-stage scales. This valuation is usually the result of a panel discussion. The following criteria are used in the valuation (Volkwein, Gihr and Klöpffer 1996), which correspond to three of the five criteria used for the UBA method:

- time criterion: The regeneration time as the time needed for restoration of a damage is used to express the time criterion
- hazard criterion: regards the danger potential of impacts
- space criterion: refers to the area related to the expected impact

Applying the three criteria together with the normalised indicator results yields a 'hierarchy level' (from 1 to 5) for each impact category. Based on this hierarchy, a hypothesis is stated of the loser of both alternatives compared: The assumed loser is the alternative with the higher environmental burdens related to the most important, top hierarchy impact category (for an example see chapter 3).

The following steps are used to verify the hypothesis:

1. A pair wise comparison of impact category indicator results from the assumed winner and loser, based on the categories' hierarchy. Similar to the UBA method, the aim is to eliminate categories where the assumed loser did not lose.
2. A similar comparison, with the difference that more than one category where the loser did not lose can be compared to a category where he did lose, provided that the latter category is high enough in the hierarchy. Indicator values of several categories are in fact aggregated.

Similar to the UBA method, the goal is to eliminate all categories where the assumed loser did not lose. If this is successful, and there remain categories where the assumed loser has lost (or the assumed winner has won, accordingly), the hypothesis is confirmed. **Fig. 2** illustrates the process of eliminating categories against each other.

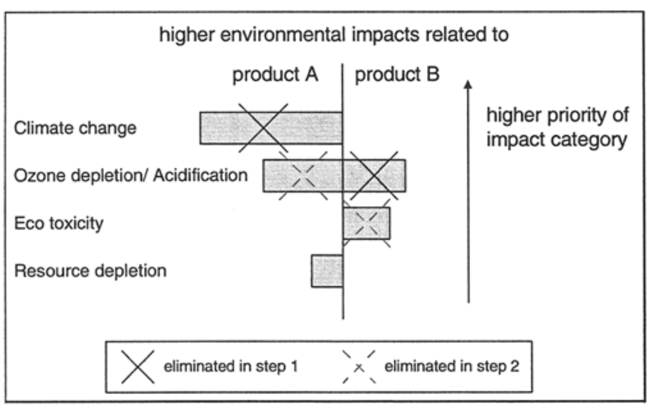



**Fig. 2:** Elimination of impact categories (example)

## 2 Proposal for a New Approach to Valuation

### 2.1 Background

The new approach to valuation presented in the following originates in a research project called Bahnkreis (see TUB 2002, Siemens 2000 and Trebst 2001). Within this project, a midpoint assessment was performed according to ISO 14042 in order to evaluate the environmental impact of components for railway applications. The decision makers and experts from the railway industry needed clear, concrete and easy to communicate results such as 'alternative A is better than B'. The results from the environmental assessment would then be comparable to the result received from the Life Cycle Costing performed simultaneously in the project. Before starting to develop a new method, a great variety of valuation methods commonly used in LCA were compared. As a result, especially regarding the variety and number of existing valuation methods, it seemed neither necessary nor efficient to develop a completely new method, thus "re-inventing the wheel a second time" (Clift 2001).

All methods compared had their specific advantages and disadvantages. The most important result from the comparison was that a combination of different valuation methods will diminish some of their individual disadvantages.

**An example:** Comparing the CAU and UBA method displayed that both methods introduce subjective, evaluating elements by ranking the environmental importance for the different impact categories. The CAU method distinguishes the three criteria temporal and local coverage and risk of the potential impact described for each impact category. Evaluating these three criteria separately, a subjective weighting of the importance of temporal versus geographical coverage or versus potential risk is avoided. But due to this cautious behaviour, the CAU method frequently does not reach a clear ranking result.

On the other hand, by using the UBA method, a definite result is obtained more frequently, but also more subjectivity is introduced in the valuation procedure, since this valuation method evaluates environmental importance by one single indicator, and for obtaining this indicator, merges three criteria (see chapter 2), assuming implicitly a similar importance for each. This is of course a subjective consideration: why should a high risk for a small group of individuals have the same value than a lower risk for a larger group of individuals?

The central idea of the valuation approach proposed in this paper is to get a definite ranking result (A better than B) by using a valuation procedure which is as transparent as possible and which, in addition, fulfils the requirements for a valuation method stated by ISO (see chapter 1). Therefore two valuation methods which fulfil ISO requirements are combined within an iterative approach, going from qualitative, semi qualitative up to completely quantitative methods until the definite result is reached. In other words, the level of subjectivity is increased until a clear valuation result is achieved. A combiation of both methods is the CAU method and the UBA method.

Both methods have been used in practice: For example, the CAU method as described in (Volkwein 1996) was applied manually for some examples within the euroMat project (Fleischer et al. 2000), where it showed its capability of providing cautious and also clear results. The UBA method has been used for nearly 5 years (Schmitz 1996).

The iterative approach described here is implemented in the software trainEE (GreenDeltaTC 2002), a software package especially developed for assessing the life cycle of complex products with a long and potentially complex life cycle, such as trains and their components. Within trainEE, the method can be performed automatically[1]. A previous version has been used within the research project 'Bahnkreis' (Siemens 2000), where applicability has been proven.

### 2.2 Method description

Fig. 3 resumes the method and describes the most important calculation steps. It is presented in a rather condensed way, for further details see (Volkwein 1996, Giegrich 1995).

#### 2.2.1 The semi-quantitative CAU method (Block V)

In case all categories favour the same alternative, no valuation is necessary in order to obtain a clear result 'alternative A is better than B', and in case both alternatives have the same values in all categories, also a ranking is neither necessary nor possible. Both cases are checked in the first steps of the method, V0 and V1. In the following, the LCIA results are normalised by the global contributions to each impact category. After that, the valuation itself starts: in the first valuation step (V1, see Fig. 3) for each impact category a rating of importance (from 1 to 5) of impact is done, considering (i) temporal and (ii) local implications of the impact and (iii) the severity of the hazard considered. A fourth criterion is the z value, given by the absolute difference of the normalised impact values of both alternatives for an impact category. It has no dimensions. These four values for each alternative constitute the semi quantitative valuation matrix, which is the starting point for the following comparison of two different alternatives A and B. For the implementation in the software tool, default values for the factors i, ii and iii for these rating factors were developed, but the user is free to modify these values when he or she considers it necessary. Then the winner for each impact category (i.e. the alternative with contributes less than this specific impact category) is stated. Afterwards, a first comparison of both alternatives is done in V2. When one alternative is the winner in all categories, a definite result is obtained and the valuation is finished. This result is called a 'Level I result'. If no clear decision can be reached at this point, levels of hierarchy are assigned to each impact category in step V3. Therefore, not only the ranking of importance of the impact category is taken into account but also the quantitative criterion z. If one category reaches higher values for the three criteria of importance and for the quantitative importance than another, this category has a higher level of hierarchy. Now the probable winner of both alternatives is determined. It is the alternative for which a lower impact is calculated for the impact category which has the highest level of hierarchy. In step V4 this hypothesis is tested: Impact categories which favour the probable loser are eliminated by impact categories which obtained a higher hierarchical level in V3 and favour the probable winner. This comparison is done in two attempts: First, in V4.1 only one to one elimination are allowed: one high level impact category favouring the winner can only eliminate one category favouring the probable loser. If all impact categories which favour the loser can be eliminated in V4.1, the hypothesis is confirmed and the ranking is a level II result. In a second, semi-quantitative attempt, in V4.2 a high level impact category of the probable winner may eliminate two or more impact categories when its z criterion is higher than the sum of the values for the z criterion for the lower level impact categories favouring the probable loser. If all categories favouring the probable loser can be eliminated, a level III result is obtained. For more details see (Volkwein 1996).

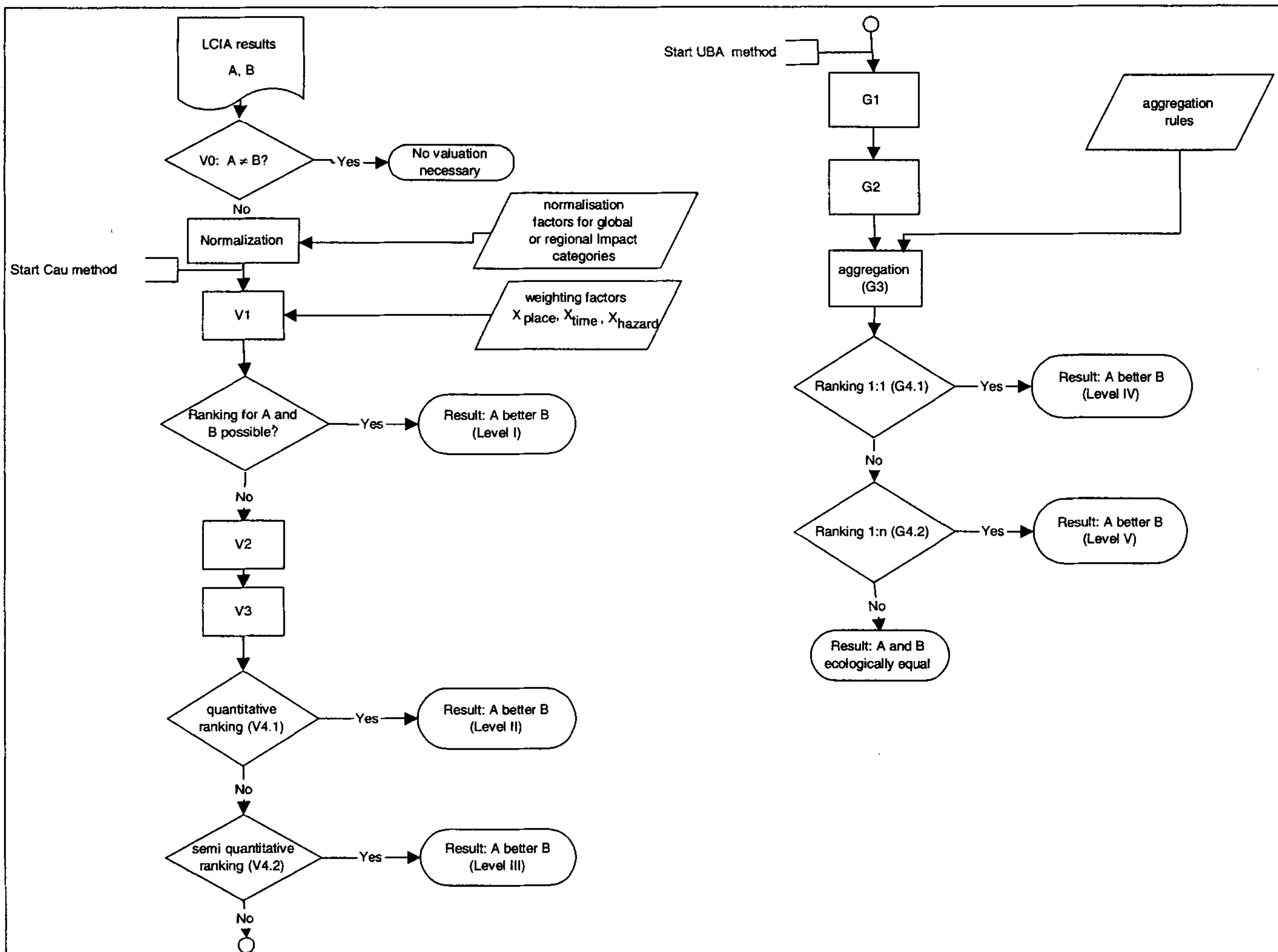
In case even after V4.2 no clear ranking of the alternatives is possible, the more rigid UBA valuation method is used.

#### 2.2.2 The UBA method (Block G)

Within this method, instead of the semi quantitative valuation matrix an 'interval judgement' is established, using only two values for the comparison of the alternatives A and B: the ecological importance of a given ecological impact category expressed in only one value and its quantitative importance value (analogue to the z value calculated in V1 of the CAU method). The quantitative importance required by the UBA method can be described by the normalised z-Value taken from the CAU method using a five level scale. This is done in step G1. The valuation criterion for ecological importance, required by the UBA method, is derived from quantitative weighting factors for location, time and hazard used in the CAU method in step G2. In doing so, the original UBA method is slightly altered (since the factors from the original UBA method are not used), for sake of consistency within the whole valuation procedure. The factors are aggregated, simply by calculating the arithmetical mean. Then the overall importance of each impact category (aggregating quantitative and environmental importance) is assigned by a valuation matrix in G3. Finally, in G4, a comparison of alternatives A and B is done. Impact categories with higher overall importance which favour one alternative are used for eliminating impact categories with lower overall importance which favour the other alternative. If all impact categories favouring one alternative can be eliminated, this alternative is the loser. A result obtained in G4 has the level IV.

When, even after this procedure, no clear ranking is possible, both alternatives are considered to have equal environmental importance. **Fig. 3** shows the iterative approach.

[1] The result within the original UBA method is text describing the result, with all its underlying assumptions. So it does not provide a result easy to communicate, as required before. The software adapted the way to present the results from the CAU method, reporting only the ranking and the categories which where eliminated against each other.




| | | | |
|---|---|---|---|
| V0 | Are the alternatives A and B different in at least one impact category? | – | – |
| V1 | Qualitative rating of the impact categories by the parameters place of effect, time and risk. | G1 | Assignment of the normalised indicator values to a five level scale for quantitative importance of the indicator. |
| V2 | First comparison of alternative A and B. Only if all results favour the same scenario, a result is given. | G2 | Assignment of impact categories to a five level scale for environmental importance, using the arithmetical mean of the values assigned in V1 for each category. |
| V3 | Assignment of levels of hierarchy between the impact categories of both alternatives considering time, place, hazard and quantitative indicator value. Designation of the probably better scenario (hypothesis). | G3 | Calculation of the overall importance for each indicator using a combination matrix. |
| V4.1 + 2 | Confirmation of the hypothesis eliminating low level categories favouring the proposed loser by higher level categories favouring the proposed winner. A first attempt eliminates categories one by one (4.1) in a second attempt (4.2) several impact categories can be eliminated by a higher one if the sum of their z values is lower. The result is confirmed when all categories which favour the supposed loser can be eliminated. | G4.1 + 2 | Ranking of scenario A and B eliminating impact categories with a lower overall importance which favour the supposed loser with higher level categories which favour the supposed winner. Similar to V4, two attempts are made. In G4.1 only one by one elimination is possible, in G4.1 several impact categories can be eliminated by a higher one if the sum of their quantitative importance is lower. The result is confirmed when all categories which favour the supposed loser can be eliminated. |

**Fig. 3:** Iterative approach of the valuation method

### 2.3 Discussion, from an abstract point

Combining valuation methods, and treating them as modules[2], has advantages and disadvantages. The most important advantage of the iterative valuation method proposed is its flexible level of subjectivity used in the valuation, since it does not establish a certain level of subjectivity considered acceptable by using one specific valuation method or another, but increases the level of subjectivity stepwise up to a level where a clear ranking between both alternatives compared is possible. This enables the LCA practitioner him- or herself to judge whether the 'price of subjectivity' paid for getting a clear ranking is too high or not. The type of LCA performed (e.g. internal use, external use), the quality of data used in the study, possible requirements of different stakeholders on the transparency and objectivity of the LCA result, and other specific considerations will play a role in this decision.

The result of the proposed valuation method is an ordinal ranking between two alternatives accompanied by the level where a result was achieved. Since both methods (UBA and CAU) produce clear and reproducible results when performed by a computer (and not by human beings), the iterative approach for a combination described in detail above is also reproducible.

The level of additional effort for the LCA practitioner who will use this methodology within the software is very low. It is required to either accept the default values for valuation or – if this is considered necessary – to change them. Since a normalisation of indicator values also is required, an additional data acquisition for global contributions to each impact category might be necessary. But since normalisation is used frequently in LCA today, gathering these normalisation factors is not considered to be specific to the valuation method described here.

A certain disadvantage of the method may show when a large number of different alternatives are compared within one study. Frequently, this is done by a pair wise comparison of each possible pair of alternatives, yielding a large number of pair wise ranking results. It is then required to rank, in a second step, all alternatives based on these pair wise comparisons. This ranking should also take into account the level of the result (I to IV see above) from the pair wise comparisons. In some cases, it may be difficult to establish a clear and reproducible order of alternatives from a large field of alternatives compared.

Some implications from the proposed valuation approach are worth being mentioned:

- The iterative valuation approach can be extended to cover even more valuation methods. For example, as a third step, a valuation method which obtains a single value (as the Ecoindicator 99 method does, in the Hierarchist, or other modes) can be added.
- Different methods combined should contain consistent value choices. For this reason, we use identical factors to assess the environmental importance of impact categories in both methods, slightly deviating from the original methods.

A certain subjectivity, and influence on the result, may be introduced by the order in which those new methods are executed. Therefore, a clear description of the 'subjectivity interface' of each method used, and a consistency check of the subjective values inherent in the methods combined, should be given in this case. Describing and documenting the subjectivity introduced helps also to make sure users know what they do when performing an automated valuation procedure.

## 3 Method Application

The method described in the previous chapter will be demonstrated by the help of a virtual case study. The case study stems from the railway industry, being a Life Cycle Assessment of two different electric motors m1 and m2 for a metropolitan train operating in the area of Frankfurt and Stuttgart in Germany. Both motors differ in product design and in their materials composition. The interpretation for the case study is performed by using trainEE, **Fig. 4** shows the form to start the interpretation.

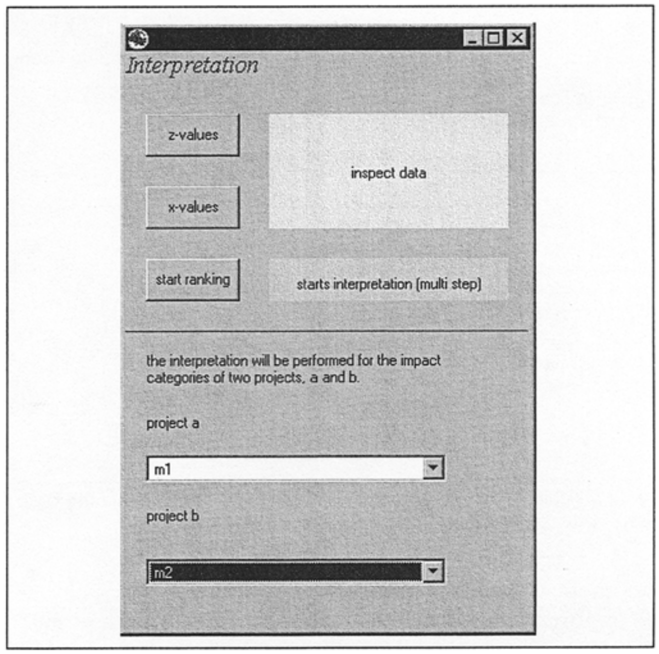



**Fig. 4:** Form to start the interpretation in trainEE

The impact assessment leads to impact indicators for both motors in eight categories. **Fig. 5** shows these results as relative values, i.e. results for m1 divided by results for m2, for each impact category. It can be seen that in this case, motor m1 scores better than m2 in the categories human toxicity potential, eco toxicity potential, and climate change potential.

The upcoming paragraph describes in detail the outcomes of different steps of the interpretation procedure.

The first check ((V0), about whether m1 and m2 are equal in each impact category) is passed, m1 and m2 are not pari in the case study.

Step (V2) (whether m1 scores equal or better than m2 in each category, or vice versa, i.e. whether there is a dominant solution or not) proves no dominant solution. Both results can also be verified by looking at Table 3: In three categories, m1 wins, in other five, m1 loses against m2.

As described in section 2.2, the remaining procedure tries to achieve a clear winner and loser by worsening the results for the assumed winner, or by improving the results for the

[2] A module defined as 'a self-contained unit or item that is used in combination with other units' (UELD 2002). (Jungbluth et al. 2000) present a 'modular LCA', where different parts of an LCA for food (transport, packaging, consumption, and so forth) are treated as modules.

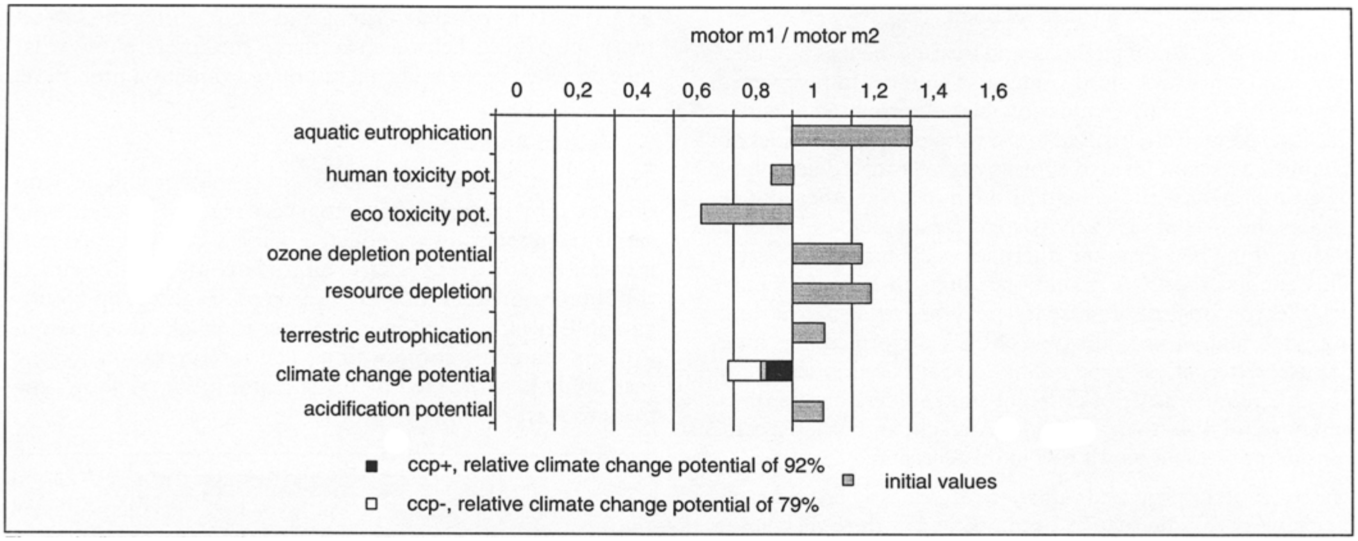



**Fig. 5:** Indicator values of motor m1 divided by those of motor m2 for eight impact categories, initial values and scenarios ccp+ and ccp-. Further explanation see text

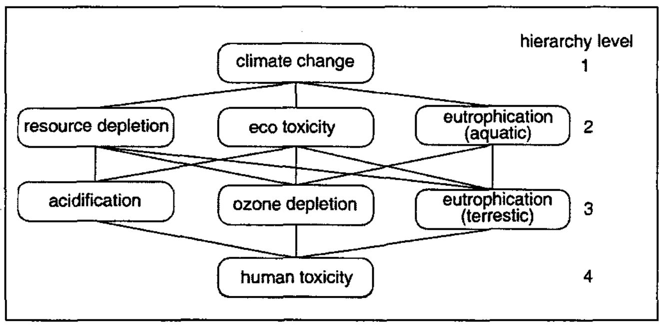



**Fig. 6:** Calculated hierarchy levels for the impact categories in the case study, initial values

hypothetical loser, respectively, based on the hierarchy in the importance of different impact categories, as described in section 2.2. The calculated hierarchy level for each impact category is shown in **Fig. 6**. Climate change potential is the top-level category, three categories get a hierarchy level of 2 and 3, respectively.

Next, step (V3) finds that m2 has a higher, i.e. worse, value in climate change potential, which is the top in the categories' hierarchy. So, it proposes m2 as 'assumed loser'. Note that it is vital within this step not to have several highest level categories with different losers and winners.

In the following step V4.1, the procedure is unsuccessful in its try to strike out categories where the loser m2 has won (see Fig. 5: aquatic eutrophication, ozone depletion potential, resource depletion, terrestric eutrophication, acidification) on a one-by-one basis. Only one of the categories (e.g. acidification, by the help of eco toxicity) can be cleared.

In the next step V4.2, aggregating several categories where m1 has lost does not change the picture. **Table 2** shows the starting values.

Only two categories (climate change and acidification) can be used for clearing the categories where the assumed winner has lost, since human toxicity has the lowest hierarchy level (and hence there is no other category with lower hierarchy's level which may be cleared by human toxicity). Eco toxicity is used for clearing acidification, and ccp's indicator value is smaller than the sum of the inferior categories. As a consequence, it is not possible to get a clear result in this valuation step.

Here, and also in the following steps, there are several different actions possible to perform (which category should be used against which other category?), with possibly a different outcome. To overcome that problem, the method is implemented so that it uses a brute force approach, i.e. it tries all possible actions, until one proves successful. This is possible because

**Table 2:** The basis for the interpretation step V4.2: Superior categories where the winner has won, and inferior categories where the winner has lost, together with differences delta z in their dimensionless z-values

| Superior impact category | Hierarchy Level superior impact category | Hierarchy Level inferior impact category | Inferior impact category | Delta z superior category | Delta z inferior category | Loser superior category | Loser inferior category |
|---|---|---|---|---|---|---|---|
| climate change | 1 | 2 | resource depletion | 1,06E-09 | 2,91E-10 | m2 | m1 |
| climate change | 1 | 2 | eutrophication (aquatic) | 1,06E-09 | 1,03E-09 | m2 | m1 |
| climate change | 1 | 3 | eutrophication (terrestric) | 1,06E-09 | 7,95E-10 | m2 | m1 |
| climate change | 1 | 2 | ozone depletion | 1,06E-09 | 1,14E-11 | m2 | m1 |
| eco-toxicity | 3 | 3 | acidification | 7,44E-10 | 6,84E-11 | m2 | m1 |

**Table 3:** calculated importance for the impact categories according to the UBA method

| Category | Loser | Calculated importance |
|---|---|---|
| climate change | m2 | 5 |
| eco-toxicity | m2 | 4 |
| human toxicity | m2 | 2 |
| eutrophication (aquatic) | m1 | 4 |
| ozone depletion | m1 | 3 |
| resource depletion | m1 | 3 |
| eutrophication (terrestric) | m1 | 2 |
| acidification | m1 | 2 |

the number of impact categories (and hence the number of possible actions) is limited, and this makes sure that no possible solution is overlooked by the valuation method.

The next step in the evaluation is a qualitative one, it is the first part of the UBA method, see Fig. 3. Similar to the previous step, climate change potential gets the highest importance of the impact categories, see also Table 3. Since motor m2 loses in this category, m2 is assumed to lose in comparison to m1, it is taken as the 'assumed loser' (steps G2 and G3 according to Fig. 3).

In the following step G4.1, the algorithm is not successful in eliminating the categories where m1 has lost. For example, using the category eco toxicity against aquatic eutrophication, and human toxicity against acidification, there remains climate change on the winner's side, and three categories on the side of the assumed loser, which evidently cannot be compensated on a one-by-one basis. That means that the assumption cannot be confirmed in this step. **Table 3** shows the calculated importance (which replaces the 'hierarchy level' from the CAU method).

Finally, in the last step G4.2, the method provides a result: Aggregating the categories where m2 has won (ODP, AP, resource depletion), all categories can be compensated by categories where m1 has won.

→ according to the method, m2 scores worse than m1. The assumption from the beginning could be confirmed, finally.

For the case study, the behaviour in the valuation strongly depends on the value in the category climate change. For example, varying the result for this category only in two scenarios 'ccp-' and 'ccp+' provides as results:

- 'ccp-': Reducing the climate change potential for m1 (in relative values: from 89% to 79% in relation to the loser m2), yields a clear result already in step V4.2. Also in this scenario, m1 wins. The algorithm does not need to go through the UBA method at all.
- 'ccp+': With a climate change potential of 92% (compared to 89% in the initial value), there are two top level impact categories (ccp and aquatic eutrophication), and, since m1 wins in ccp and m2 in aquatic eutrophication, the application of the CAU method is not possible. The algorithm skips the CAU method, and gets a clear result by performing the UBA method. Also, in that case, m1 wins.

Values for both of these scenarios are shown in Fig. 5, indicated as ccp+ and ccp-. Note that indicator values for the other categories remain unchanged compared to the initial case study. This demonstrates clearly that the method is sensitive to changes in important impact categories.

## 4 Conclusions and Outlook

This text presents a new method to perform a valuation of impact category results in LCAs. The method consists of a combination of existing, unique valuation methods described earlier in literature, which were broadly used in LCA case studies in Germany, and which both are of a rather non-aggregating nature, and were designed to be performed by LCA experts.

The iterative nature of these methods and especially the combination of these methods, helps in achieving a valuation result for the LCA with not more subjective and aggregating elements than necessary. Subjective elements are clearly separated from others.

The method is implemented in a computer software that runs on a PC. Besides constants used within the method (e.g. normalisation factors), the software needs as input solely indicator values from the Impact Assessment, and it provides as output the valuation's result: Which of both products compared scores better in the Impact Assessment. To better help the user to understand the result and to use it appropriately, this statement is accompanied by the information in which step of the algorithm the result was achieved, especially how many aggregating steps were applied, and which subjective elements introduced.

The implementation makes the application of the method easier by transferring routine work (building hierarchy levels, eliminating different categories, and so forth) from LCA experts to a machine. With a given valuation of impact categories, and given indicator results, the method ensures a reproducible result, and prevents erroneous steps in a rather complicated valuation procedure. It further helps largely in hiding the complexity of the method from the user, since for the user, the method needs only a single step and is in that respect comparable to, e.g., weighting methods.

The implementation also allows performing a Monte Carlo simulation of the valuation method, which gives access to a thorough and systematic analysis of the method's behaviour with uncertain data, and it facilitates studying the method's sensitivity / robustness by introducing small changes in indicator values (Ciroth 2002). Care has to be taken to make sure users know what they do when performing an automated valuation procedure.

The method is ready to be used as such; in addition, it offers rich possibilities for future extensions:

1. **Uncertainty:** Some commercial LCA software packages already provide an uncertainty assessment for the inventory and impact assessment, and provide information on the uncertainty in indicator values. It is desirable for the

method to be able to handle this information, i.e. to be able to explicitly deal with uncertainty. This would also help to make the method more stable to uncertainties introduced in important categories (such as climate change in the case study presented above).

2. **Normalisation factors:** To ensure a worldwide applicability, especially with regard to the ongoing life cycle initiative, the method's value will increase if it provides normalisation factors, and factors describing the importance of impact categories, on a worldwide level, or, even better, on a level of different regions in the world where these factors matter.
3. **Toolbox:** The method may be part of a toolbox of modular valuation methods, that are implemented in a software and may be combined by LCA users according to their needs and the goals of a specific case.

The software will also be made available as a stand alone solution, so that it may be used in any LCA case study with midpoint impact assessment.

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